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**Factors in Joint Design Using
Adhesives for Metal Bonding**

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The factors leading to the selection of adhesives for bonding metal and the limitations of these adhesives are given. The data represented by the various graphs indicate factors which need to be known in most problems of design. They are frequently different from those considered in designing with nonorganic materials.

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Factors in Joint Design Using Adhesives for Metal Bonding

HISTORY

The history of adhesives is summarized by Del Monte (1).¹ Up to this century, animal, vegetable and fish glues predominated. Darrow (2) reviews the art of gluing as portrayed by the Egyptians and Romans. Egyptian murals and veneered caskets in our museums indicate the early origin of the art of gluing. The first commercial glue plant was founded in Holland in 1690. The first glue factory in the United States was started in 1808 by Elijah Upton. Up to the twentieth century, the great majority of glue applications were in the manufacture of furniture.

Del Monte (1) notes some of the outstanding adhesive developments in the United States. The list is significant in that it denotes the trend toward the synthetic-resin adhesives. World War II brought out a number of new large-scale applications to boat, aircraft and building construction. Laminated keels for small boats; resin-bonded plywood monocoque constructions for wings and fuselages, droppable fuel tanks; and metal to metal bonded aircraft assemblies.

Interest in the possibilities of synthetic resin and rubber adhesives for the bonding of metals was awakened in this country by the development of "Cycleweld" in 1942. During the war, aircraft subassemblies such as wing flaps, stabilizers, heating ducts, bomber floors, and the like, were manufactured. A few years earlier, the "Redux" process developed by Aero Research Ltd. in England was announced. The DeHaviland Aircraft Co. Ltd., first used "Redux" in the Hornet and Mosquito aircraft during World War II. Progress in metal to metal adhesive bonding has progressed rapidly in the aircraft industry since the last war. The B-58 "Hustler," for example, uses a great amount of bonded construction. In automobiles, adhesives are used extensively in brake linings. The use of adhesives can well be expected to expand into other metal-bonding applications in the future.

WHY USE A BONDED JOINT?

The reason an adhesive bonding operation is used can usually be traced back to one or more of the following potential advantages:

¹ Numbers in parentheses designate References at the end of the paper.

1 In adhesive bonds the load is more equally distributed than in other type joints. Smoother contours are produced; gaps and voids are minimized. This minimizes stress concentrations which in turn may produce better fatigue properties and may allow a reduction in metal thickness.

2 Adhesives are elastic enough to absorb stresses created by flexing and differences in coefficients of expansion.

3 Adhesives can join dissimilar metals and materials and in some cases are the only method of joining.

4 Bonded joints dampen vibrations.

5 Cost savings can sometimes be effected by eliminating fastener costs, reduce metal forming and machining operations.

6 Large areas can be bonded in a relatively short time.

7 A general reduction in weight can be accomplished; i.e., reduced metal thickness and elimination of fasteners.

8 The adhesive bond can provide electrical insulation and thus minimize galvanic corrosion.

9 Does not embrittle aluminum or magnesium or tend to warp steel as welding may do.

10 Eliminates the need for high temperatures as used in welding.

11 Leaves good surfaces for organic coatings.

12 Adhesives provide a sealing action in addition to bonding.

13 Give easier alignment of joined parts where alignment is critical.

Reasons that may prevent the use of adhesive bonding are represented by the following:

1 Heat and pressure may be needed to cure the adhesive and this may make it less feasible than another method of joining.

2 Jigs and fixtures for applying the heat and pressure may be very expensive.

3 Application of some adhesives is susceptible to high humidity and/or low temperatures.

4 There is not too much background in durability and permanence tests.

5 It is a basic fact that organic compounds are not as stable as metals at elevated temperatures.

6 Strong and reliable bonds can only be effected if the surfaces to be bonded are clean.

7 Stronger and more reliable bonds can be

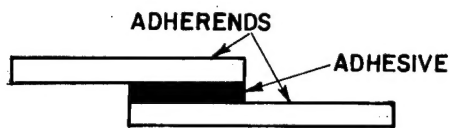


Fig. 1 Lap joint

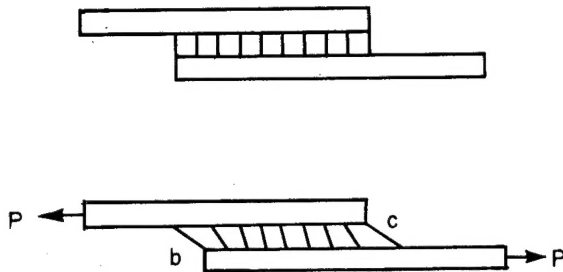


Fig. 2 Differential strain in a lap joint

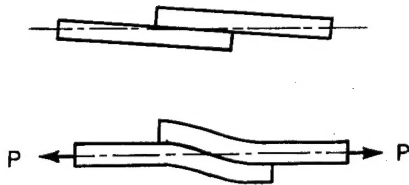


Fig. 3 Bending of adherends in a lap joint

effected if the parts to be bonded are closely mated.

8 The time required to form a bond may add unreasonable cost to a product.

9 Inspection and nondestructive testing are difficult or impossible.

10 Other methods of joining may be stronger.

ADHESIVE JOINT DESIGN

Introduction. Parts to be bonded with adhesives must be designed properly to obtain the maximum strength properties. Factors dictating the joint design are dependent upon the direction and magnitude of the load and whether the stress will be applied continuously, short term or intermittently.

Stress Distribution in Lap Joints. Most adhesives used for structural metal to metal bonding are relatively rigid but have some elastomeric properties. They are strongest in direct shear or tension and weakest in peel and cleavage. A large portion of the engineering data on metal to metal bonds have been obtained as shear strengths with plain lap joints, Fig. 1. This type of joint is easy to make and is quite common in manufac-

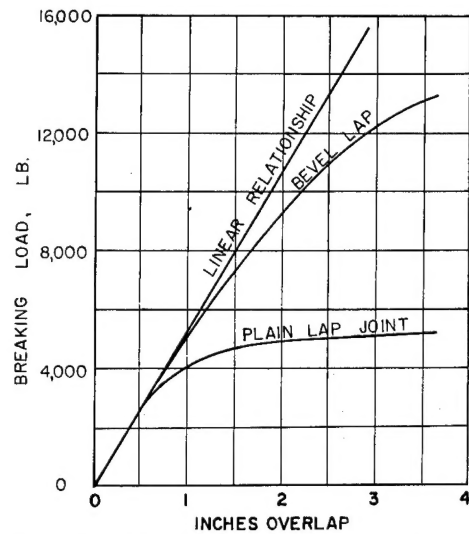


Fig. 4 Breaking loads in lap joints with varying amount of overlap

tured items using adhesives since adhesive bonds exhibit high strengths when stressed in shear. Stress concentrations are produced in the bonded joint just as they would be in an unfilleted weld or braze. Two causes are mainly responsible for these stress concentrations:

- 1 Differential strain of the joined members.
- 2 Bending of the joined members.

Referring to Fig. 2 (3), each member bears the full load P just before the joint and transmits it gradually to the other through the adhesive. Thus the stress of the upper adherend will be highest at b and will gradually diminish until at c it is zero. However, in the lower member the stress will be greatest at c and diminish to zero at b . When the members obey the laws of elasticity, these members will develop strains proportional to the stresses. This results in higher stresses in the adhesive at each end of the overlap. The members of the lap joint are necessarily offset by the amount of their thickness. This eccentric loading gives rise to a bending moment which will tend to pull the members apart. Under this moment the members will yield if the applied load is great enough. This is shown in Fig. 3. The tearing or peeling stresses are concentrated at the ends of the overlap and combined with the effects of differential straining considerably reduce the strength of lap joints. The Goland and Reissner theory (4) indicates that these concentrated tensile stresses at the edges of the overlap can reach 4.3 times the mean member stress with a rigid adhesive. The concentration of stresses at the ends of the overlap decreases somewhat as the flexibility of the adhesive increases but it is still the critical area in the bond. As a result, the observed failure loads on metals which can deform in this way are substantially below the true strength of the

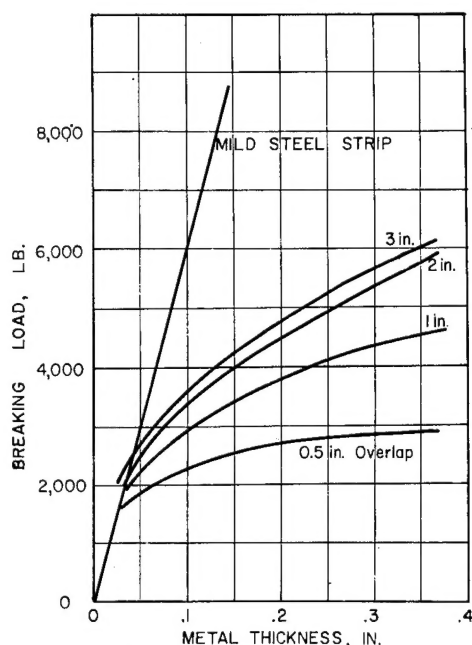


Fig. 5 Effect of thickness and overlap on the ability of bonded lap joints to carry a load

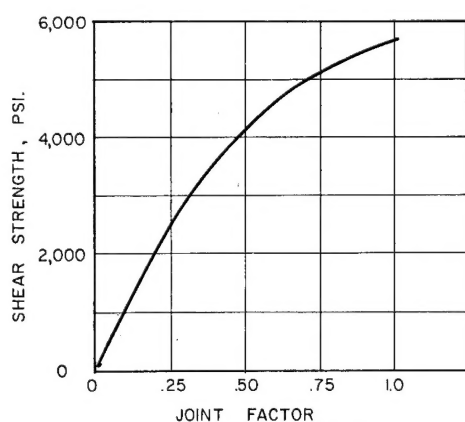


Fig. 6 Joint factor, $\sqrt{\text{metal thickness/length of overlap}}$, brings data on mild steel, Alclad and Dural together on one curve

adhesive. The high proportion of the failure load carried in the edges of lap joints is illustrated by the fact that an adhesive showing an apparent bond strength of 3000 psi with a 1-in. overlap, will fail at about 2500 lb when the edges of the lap are bonded with a $1/4$ -in.-wide band of adhesive on each edge. The center half of the lap, thus, contributes only about $1/6$ of the total strength. This illustration indicates also that the apparent bond strength is not proportional to the length of overlap. DeBruyne (5) has shown this to be the case.

Fig. 4, adopted from DeBruyne's data, shows a representative curve of this phenomenon. Each

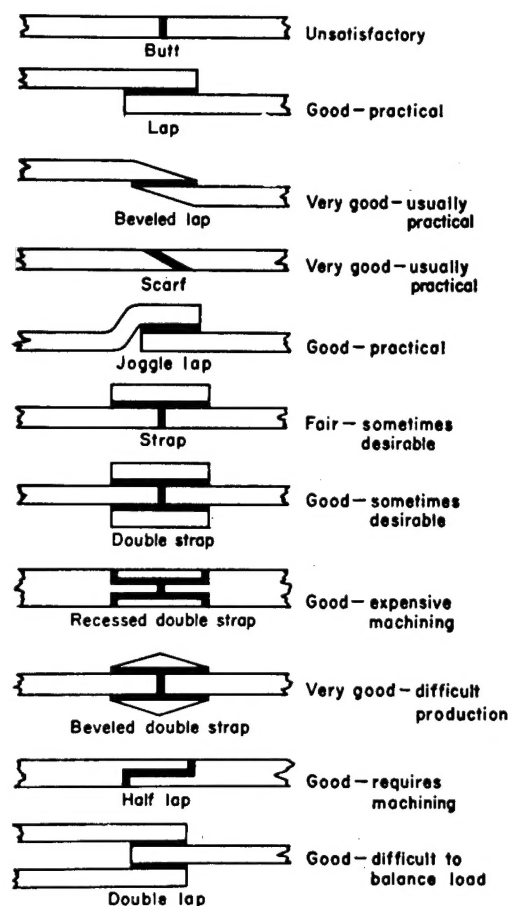


Fig. 7 Adhesive bonded joint designs

adhesive will form a different curve but the general characteristics are similar. The strength of a lap joint also depends on the thickness of metal and the yield strength of the metal, as shown in Fig. 5. The thickness of the metal and the overlap length have been combined into the term joint factor and related to failing stress by DeBruyne (5). A smooth curve, Fig. 6, is obtained when joint factor is plotted against failing stress. The Glenn L. Martin Co., working with aluminum alloys, has determined that the optimum overlap length is approximately twenty-five times the metal thickness for the particular adhesive they were working with, a phenol formaldehyde-vinyl butyral tape. DeBruyne points out (5) that the strength of a lap shear joint is directly proportional to the width of the joint. The width and overlap factors have been verified in our laboratory.

Other Type Joints. A variety of joint designs have been proposed and are illustrated in Fig. 7 (6). The scarf and the bevelled lap are the most efficient because they reduce the concentration of stresses at the ends of the overlap. Fig. 4 shows the strength relationship of the

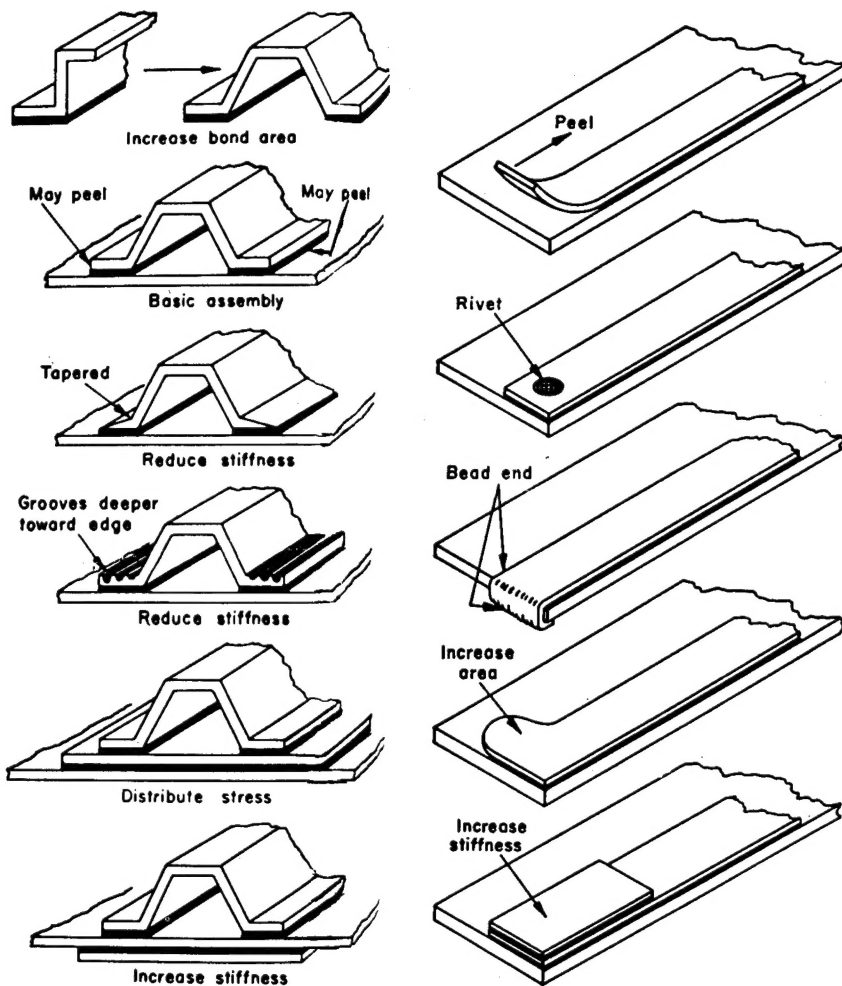


Fig. 8 Joint designs to minimize peel

bevelled and plain lap joints. In production, however, the bevelled and scarf joints would be expensive and are therefore not generally recommended.

Effect of Peel and Cleavage Stresses. Peel stresses must be kept to a minimum for properly designed adhesive bonded joints. Fig. 8 (6) illustrates some of the steps that can be taken to minimize them.

As mentioned previously, it is most desirable to bond the parts so that the adhesive is stressed in shear. In heavy sections, a bond that is placed in pure tension should be satisfactory. However, cleavage stresses usually result which reduce the strength of the joint. Fig. 9 (6) illustrates methods of minimizing cleavage.

STRENGTH PROPERTIES OF ADHESIVE BONDS

Most strength data on adhesive bonds have been obtained with simple lap joints. Further-

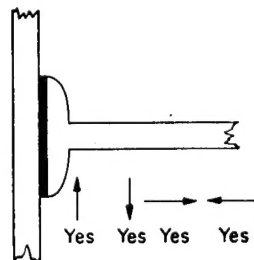
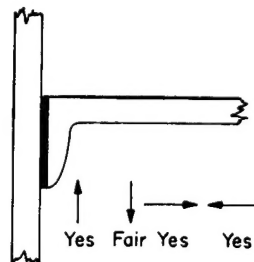
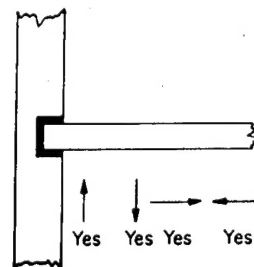
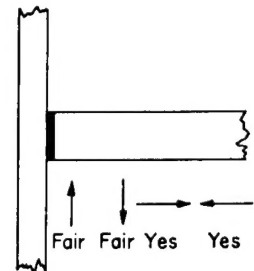
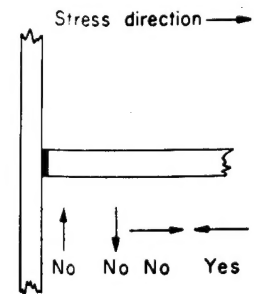


Fig. 9 Joint designs to minimize cleavage

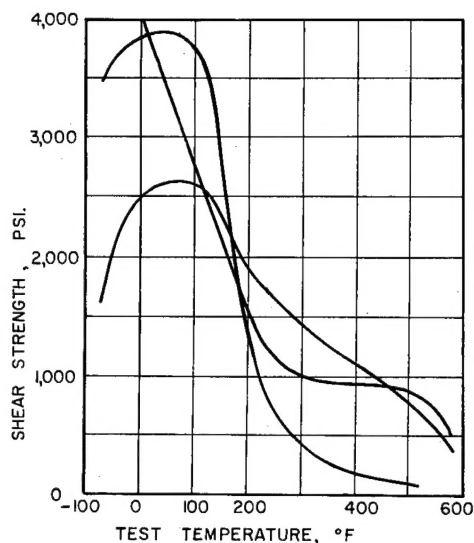


Fig. 10 Strength of an adhesive is a function of temperature of its environment. Three different performances are illustrated by three different formulations of modified phenolic adhesive

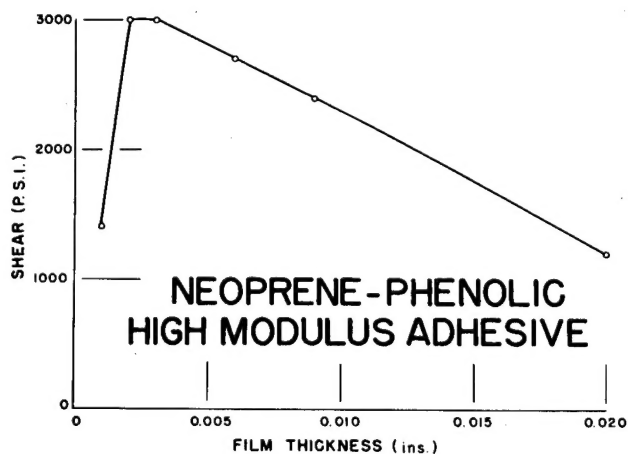


Fig. 11 Effect of bond film thickness of a high-modulus adhesive on shear strength

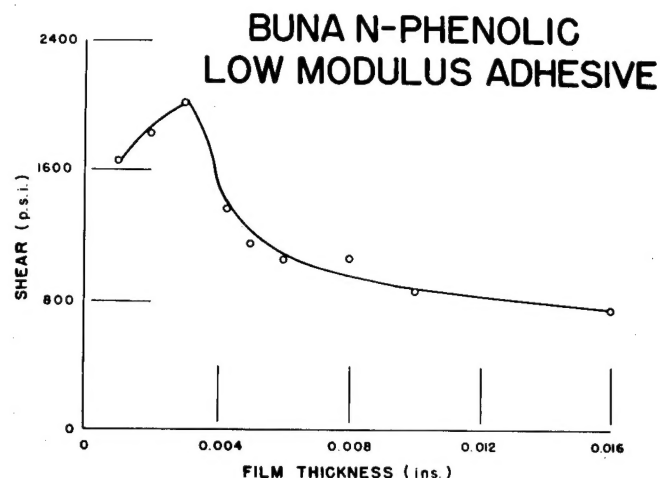


Fig. 12 Effect of bond film thickness of a low-modulus adhesive on shear strength

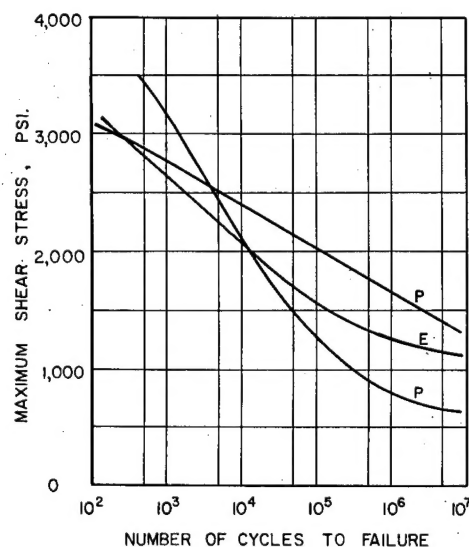


Fig. 13 Fatigue failure of two modified phenolic adhesives, P, and one epoxy adhesive, E

more, most of the data has been obtained with aluminum or aluminum-alloy adherends because the great majority of structural adhesive applications to date have been in the aircraft industry. There is very little data on steel-to-steel bonds.

The effect of temperature on shear strength is shown in Fig. 10, based on the work of Eickner, Olson, and Blomquist (7). They found, as did Kuenzi (8), that the thermosetting phenolic-synthetic rubber adhesives tend to show stronger bonds at high temperatures than do other adhesives. The work toward better high-temperature adhesives is receiving very much attention largely

because of the demands of the aircraft and missile industry. More recently epoxy phenolics, high functionality epoxies and silanes have been considered. Forest Products Laboratory has been studying the effects of temperatures from -100 to +1000 F on the strength properties of seven commercial metal bonding adhesives. Lap shear, long-time load, peel and fatigue tests are involved. Tensile shear strengths of 2300 psi at 350 F and over 1100 psi at 500 F have been reported.

The strength of a lap shear joint is also dependent upon the thickness of the glue line. Koehn (9) has shown that an optimum glue line thickness

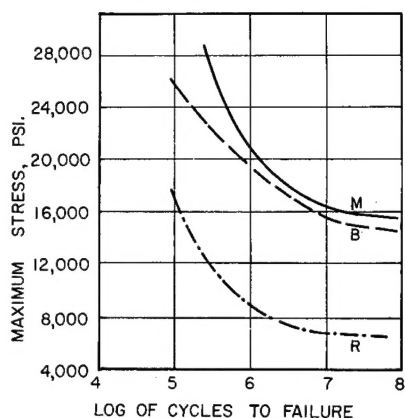


Fig. 14 Fatigue failure of metal alone-M; bonded joint-B, riveted joint-R. All three used 6.3-in-wide metal, 0.031 in. thick. Bonded and riveted overlaps were 1.5 in. Rivet diameter 0.012 in.

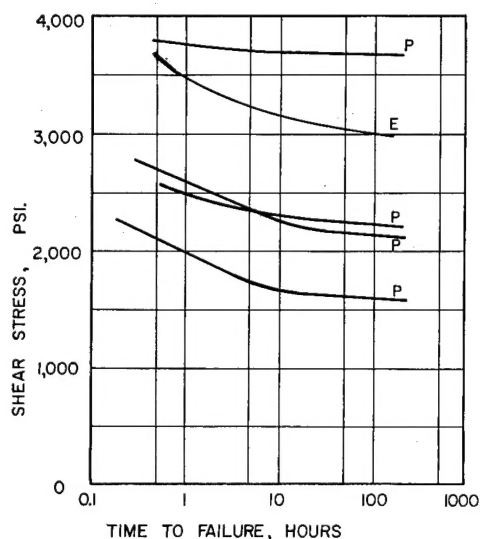


Fig. 15 Stress rupture of aluminum to aluminum bonds at 72 to 76 F. P-modified phenolic adhesives; E-epoxy adhesive

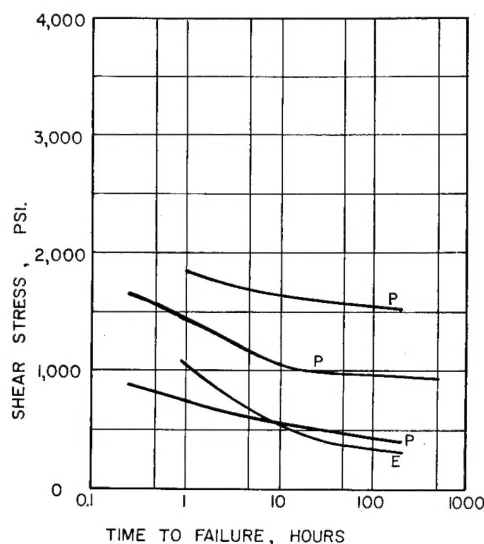


Fig. 16 Stress rupture of aluminum to aluminum bonds at 178 to 182 F. P-modified phenolic adhesives; P-epoxy adhesive

stress levels were in the metal rather than in the adhesive bond. Unpublished work in our laboratory has shown that the fatigue strength at 4×10^6 cycles is 35-60 per cent of the ultimate tensile shear strength and is dependent upon the test frequency.

Fig. 14 (11) compares the fatigue strength of a bonded joint with that of a riveted joint. In this test the bonded joint was almost as strong as the base metal.

The improvement of bonded structures over riveted structures in fatigue in aircraft is a major advantage of bonded joints. On a fatigue test of a helicopter blade skin with adhesive bonded stringers and local rivet reinforcements for attaching the skin to the rib structure, failure took place by a crack developing at a riveted joint after 150 million cycles of reversed stress (12). The adhesive bond had not failed. C. J. Moss (13) has described other fatigue tests made by the Bristol Aeroplane Co., Ltd., in which Redux-bonded panels were in perfect condition after six times as many reversals as caused cracking in riveted panels. Another example is in a test panel for the B-36's made by Consolidated Vultee. The number of cycles to failure for three methods of attachment are as follows: Spot welding 12×10^6 cycles; riveting 18×10^6 cycles; adhesive bonding 27×10^7 cycles. The failures of the spot-welded and riveted sections were due to stress concentrations developing at the weld or rivet holes.

The effect of long-term loads or stresses on lap shear joints is shown in Figs. 15 and 16,

exists. The optimum thickness appears to be about 4 to 6 mils but varies with the adhesive used, Figs. 11 and 12 (9). More recent experience indicates epoxy adhesives are not as critical in glue-line thickness as those reported by Koehn.

The fatigue strength of lap shear joints is shown in Fig. 13 (10). The load was cycled between the tensile shear loads indicated on the graph and 10 per cent of that load. It was found (10), that the fatigue strengths at -65 to -70 F are very nearly equal to those at room temperature. Also, most of the failures at the low

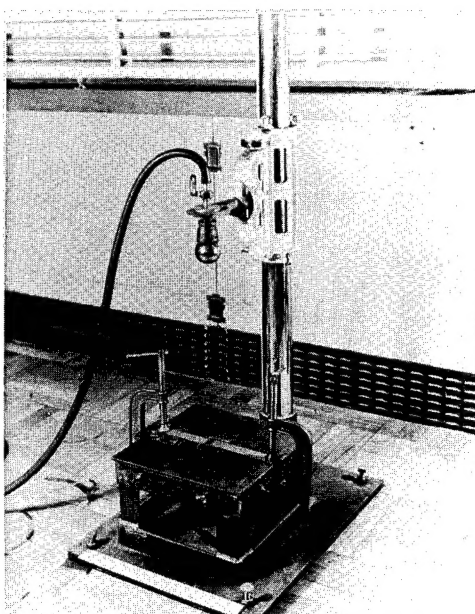


Fig. 17 Apparatus for falling-ball impact test

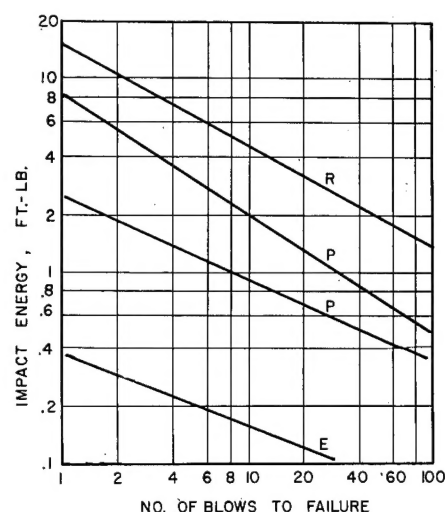
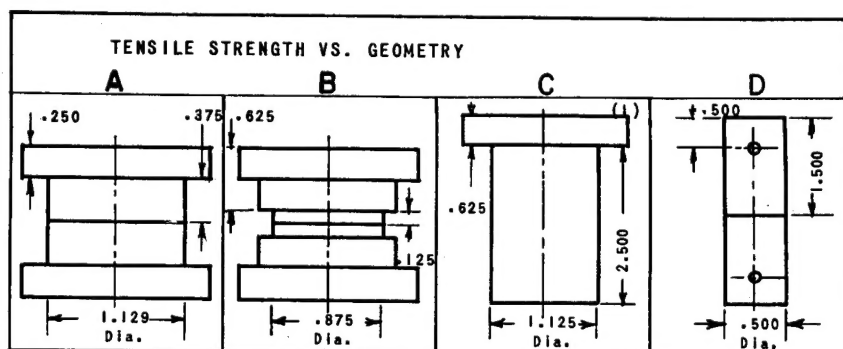


Fig. 18 Impact resistance of lap joints to a dropping ball; impact energy level versus blows to visible failure. Three energy levels were used for each adhesive. Adhesive R was a modified rubber, P-modified phenolics and E an epoxy resin



(1) Only one half of test specimen shown

Fig. 19 Effect of test specimen geometry on tensile strength

adapted from Eichner's work (10). Even at 180 F some adhesive bonded joints are able to withstand high stresses for long periods of time.

Work in our laboratory on steel adherends has shown stress-rupture limits of 30-45 per cent of ultimate strength with rubber-modified phenolic adhesives and up to 75 per cent with an epoxy adhesive.

The Nation all Luchtvaart Laboratorium, Amsterdam (11), found that Redux-bonded joints will withstand at least 75 per cent of the short-time breaking bond at room temperature for long periods. Their tests were conducted for times up to 6 months.

The effect of impact on adhesive bonded joints has been determined on lap-shear specimens

in our laboratory using a falling-ball test, Fig. 17. Results obtained by this test method are shown in Fig. 18. It is felt that this test is a very good method of comparing the impact resistance of various adhesives.

It has been mentioned that structural adhesive joints should be designed to minimize the effect of peel and cleavage. Peel tests are usually conducted with one flexible member bonded to a rigid member and are tested by peeling the flexible member at an angle of 90 or 180 deg. Recently, ASTM has prepared a new test method for peel, based on a climbing drum. For structural adhesives the peel strengths are in the range of 10-25 lb per in. of bond width. The high-modulus, rigid adhesives such as unmodified epoxies

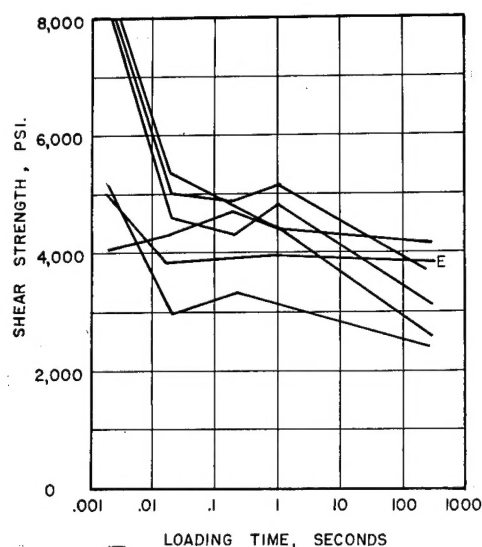


Fig. 20 Effect of rate of loading on shear strengths of aluminum-to-aluminum bonds at room temperature. All adhesives were modified phenolics except one which was an epoxy and is designated E

and phenolics have lower peel strengths than do lower modulus adhesives such as rubber-modified phenolics. Koehn (9) has shown that peel strengths increase as the bond thickness increases. DeBruyne (11) has stated that the peel test is preferred to lap-shear tests as a production control test because it is much more sensitive to changes in adhesive, surface preparation, and so on.

Adhesive bond strengths when tested in pure tension are usually considerably stronger than when tested in tensile-shear. The introduction of cleavage, however, can greatly influence the apparent tensile strengths. Koehn (9) points out that an adhesive that will demonstrate a tensile strength of 6000 psi with one type of tensile specimen will fail at about 2700 psi with another type of tensile specimen in which cleavage is apparently introduced. Also, the Naval Ordnance Laboratory (14) has shown, Fig. 19, and Table 1, the variation in apparent tensile strengths that can be obtained with differently designed specimens.

Wittman (15) has conducted tests relating tensile-shear strength at room temperature to the rate of loading of the specimens. His results, presented in Fig. 20, indicate that for the more rigid adhesives, phenolic-vinyl butyral and epoxy, the tensile-shear strength remains fairly constant as the rates of loading increases. The shear strength of the less rigid adhesives, phenolic-synthetic rubber, increase markedly as the

TABLE 1 TENSILE STRENGTH VERSUS GEOMETRY

DESIGN	A	B	C	D
Bonded area, square inches	1.0	0.601	1.0	0.196
Grip flange opening, inches	1.552	1.140	1.140	-
Thickness of grip flange, inches	0.187	0.250	0.250	-
Tensile strength, psi	3540	5740	7870	8710

loading rate increases. A round-robin test program conducted by ASTM Committee D-14 on Adhesives found that steel and aluminum tensile-shear specimens showed very little change in strength when tested at rates of stress from 600 to 2000 psi per min. It was also shown that it is not possible to express one rate of stress as being equivalent to a rate of strain for adhesives of different elastic modulus.

DURABILITY AND PERMANENCE OF ADHESIVE BONDS

Introduction. The bond strength determined shortly after a bond has been formed is not an indication as to what the strength will be after aging or exposure to various environments.

There is not very much information available on the permanence of metal to metal bonds, but there is an abundance of data on the wood to wood bonds. Most of the metal to metal data pertains to aluminum. Data on steel to steel bonds are very meager.

Metal to Metal Bonds. Forest Products Laboratory (16) started outdoor weathering tests in 1953 in six locations from Alaska to Panama. Some adhesives have shown good performance after 3 years' exposure in Florida and the Canal Zone while other adhesive deteriorate. Exposure in Madison, Wis., New Mexico and Fairbanks, Alaska, was generally less severe than the Florida and Canal Zone exposures. Forest Products Laboratory is continuing this work (17). Painted steel to steel bonded specimens have been exposed on our factory roof in Milwaukee for over 5 years with very little change in strength. In some cases an increase in strength was found.

Military Specification Mil-A-5090B requires adhesive bonds to withstand salt-spray exposure and immersion in water, ethylene glycol, anti-icing fluids, oils, and various fuels. In general, many adhesives meet these requirements. Unpublished work in our laboratory has shown that 72 hr in boiling water is a good accelerated test for comparing adhesives for water resistance.

Wood to Wood Bonds. Wangaard (18) has shown the relative durability of glued joints in unprotected plywood panels under outdoor weathering

conditions. These results indicate that there is very little actual deterioration of phenol resin-bonded plywood after 10 years of outdoor exposure. Wangaard, in the same report, gives considerable data from ten laboratory exposures ranging from continuous water soak, high and low-humidity cycling to soaking-drying cycling for periods ranging from 1 1/2 to 8 years. He concluded that "in general the strength of a wood glue joint (using phenolic resins) is largely limited by the ability of the wood itself to resist the conditions of exposure."

Metal to Wood Bonds. The durability of glued birch plywood to clad aluminum and cold-rolled steel joints was studied by Eickner (19). Specimens were subjected to twelve exposure conditions including outdoor weathering for periods of times up to one year.

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